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Wind erosion quantity and quality of an Entic Haplustoll of the semi-arid pampas of Argentina

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Abstract

Wind erosion is said to be an important degradation process of soils, but little is known about the magnitude of this process and its effect on soil nutrient transport in Entic Haplustolls of the semi-arid Pampas of Argentina. The objective of this study was to measure the rate of wind erosion and the concentration of nitrogen and phosphorus in the sediment originating from different tillage systems: conventional tillage (CT), vertical tillage (VT), and no-till (NT), for two different crops of the semi-arid Pampas of Argentina. Measurements of airborne sediment were carried out in an 8 ha field using Big Spring Number Eight (BSNE) samplers, in two periods of 1998 and 1999, after seeding sunflower (*Helianthus annus*) and rye (*Secale cerale*). Losses and accumulations of material were detected. Losses varied between 4 and almost 900 kg ha^{-1}, and accumulations between 3 and 580 kg ha^{-1}. Wind erosion was higher in 1999 than in 1998 in all tillage systems, due to higher wind speeds and lower plant residue coverage of the first measurement period. In 1999, erosion was lower in plots with higher plant residue coverage (NT against CT), and in 1998 sediment accumulation was observed in these treatments. Nitrogen concentration in the sediment collected at greater heights increased and phosphorus concentration decreased with wind speed. This was due to the accumulation of nitrogen in the coarsest aggregates and of phosphorus in the finer aggregates. The nitrogen enrichment of the sediment varied between 2 and 5, while the phosphorus enrichment varied between 1.5 and 8. The nitrogen enrichment increased and the phosphorus enrichment decreased with wind speed. Lower wind-speed storms will erode relatively more phosphorus than

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nitrogen. When high wind-speed storms occur, nitrogen becomes more susceptible to erosion. Wind speed is the variable that may regulate the amounts of nutrient loss.

Keywords: Wind Erosion; Erosion quantity; Erosion quality; Semi-arid regions; Loess soils

1. Introduction

Wind erosion is said to be one of the most important degradation processes in many regions of the world. In the semi-arid Pampas of Argentina (SAP), the magnitude of this process has been indirectly demonstrated by several authors, but little is known about its qualitative and quantitative extent. In the SAP, 60% of total soil nitrogen and phosphorus losses after 86 yr of cultivation were attributed to wind erosion and only the 40% to crop extraction (Zanotti and Buschiazzo, 1997). It has been also demonstrated that non-eroded Haplustolls were transformed into Ustochrepts after wind erosion, due to loss of organic matter and decreased thickness of the A-horizons (Buschiazzo and Taylor, 1993).

In Argentina, the first attempt to measure wind erosion amounts by means of field measurements was carried out by Buschiazzo et al. (1999). These authors demonstrated that the wind erosion of a bare Entic Haplustoll was lower than that of a Typic Ustipsamment during two storms of different wind intensities. It is not known how the most common tillage systems used in the SAP affect wind erosion.

Tillage systems can modify wind erosion due to short-term changes in soil surface roughness (Fryrear, 1984), soil crusting (Zobeck, 1991) and aggregation (Zobeck et al., 2004) or by modifying the soil cover with plant residues (Findlater et al., 1990; Ghebreiyessus and Gregory, 1987). In the long-term, tillage practices can increase or decrease soil organic matter contents by affecting soil structure and the soil susceptibility to erosion by wind and water.

The spring and summer months are the most critical for the occurrence of wind erosion in the SAP. This happens because winds in these seasons have higher velocities (Casagrande and Vergara, 1996) and the soil is mostly bare because of soil preparation for the seeding of summer crops with diskers and harrow diskers. The no-till (NT) system, recently adopted by many farmers in the region, decreases the amount of eroded soil (Buschiazzo and Aimar, 1998).

There have been limited studies of the nutrient content of windblown sediment. These studies have included investigations of ex situ bulk surface soil tests in the laboratory (Hagen and Lyles, 1984) and naturally eroded soils in the field (Zobeck and Fryrear, 1986a, b; Zobeck et al., 1989; Sterk et al., 1996; Bielders et al., 2002). Little is also known about the effect of wind erosion on the rate of nutrient losses by soils under different tillage systems. Generally, soil transported by wind is enriched in plant nutrients compared with the parent soil (Zobeck and Fryrear, 1986b; Larney et al., 1998; Bielders et al., 2002). Zobeck et al. (1989) found an increase in nutrient concentration with increasing heights above the soil surface, which was attributed to the amount of finer sediments at these heights.

The objective of this study was to measure the rates of wind erosion and the concentration of nitrogen and phosphorus in wind-blown sediment in different tillage systems and under different soil surface cover produced by two different crops of the SAP.

2. Materials and methods

2.1. Experimental site

Wind erosion was measured in a 32.1 ha field located near Santa Rosa, La Pampa, Argentina (36°30′S latitude and 64°30′W longitude).

Mean annual temperature of the region averages 16 °C and mean annual rainfall is 550 mm. Mean annual wind velocity of this region varies between 10 and 15 km h^{-1}, and wind blows more frequently from the north and the south-west (Casagrande and Vergara, 1996). The highest wind velocities occur between late winter (August and October) and spring months and average 20–25 km h^{-1}, with frequent peaks of 50–60 km h^{-1}. The soil of the experimental site was a fine sandy loam Entic Haplustoll with an A–AC–C_1–C_{2k} horizon sequence. The organic matter content (Walkley and Black, 1934) of the A-horizon was 1.75% and the granulometric composition, determined with the pipette method was 12.2% clay and 19.7% silt. The mean grain diameter of the soil is 85 μm.

2.2. Field measurement

Field measurements of airborne sediment were carried out with Big Spring Number Eight (BSNE) sediment samplers (Fryrear, 1986) in two periods: between November 25 (sunflower—*Helianthus annus*—summer seeding in a rye—*Secale cerale*—straw) and December 14, 1998 (soil covered by sunflower canopy), and between August 3 (rye winter seeding in sunflower straw) and November 10, 1999 (soil covered by rye canopy). Canopy density was measured with the line-transect method.

The experimental site was divided in three plots of 10.7 ha each. The contiguous surrounding fields (500 m width) were 100% covered with alfalfa (*Medicago sativa*) permanent pastures and wheat (*Triticum aestivum*) during measurements. The following tillage systems were used in each plot since 1996: (1) conventional tillage (CT), used a harrow-disker for seedbed preparation. The soil was plowed to a depth of 18 cm for seedbed preparation of the summer sunflower crop between August and September after the first spring rains. Planting of the summer crop was done in November with a deep-furrow seeder, which produced a W–E-oriented roughness. The soil was plowed to a depth of 18 cm for seedbed preparation of the winter rye crop in February. Seeding of the winter rye crop was done in June with a conventional seeder, (2) vertical tillage (VT), was similar to CT but included vertical plowing with chisels to a depth of 23 cm, after the first plowing with the harrow disker, and (3) no-till (NT) consisting in a chemical fallow with glyphosate and planting with NT seeders. The crop sequence in all tillage systems was the same: rye–sunflower. Soil cover with plant residues and surface roughness are detailed in Table 1, the main characteristics of windstorms are detailed in Table 2, and heights and optical densities of growing crops are detailed in Fig. 2. The soil cover with plant residues was measured with the line-transect method, surface random roughness was measured with the chain method (Saleh, 1993) and oriented roughness with the ridge height and space method of Zingg and Woodruff (1951).

Three BSNE samplers were placed on poles at heights of 13.5, 50 and 150 cm at all sampling points. The spatial distribution of sampling points is detailed in Fig. 1.

Table 1
Soil surface roughness and residue cover at experiment start and end of a summer- (sunflower) and a winter crop (rye) in three tillage systems

Soil surface roughness (cm)			
Date	Tillage system		
	VT	NT	CT
Sunflower (1998, summer crop)			
Soil residue cover at seeding time (%, and residue type)	0	80 (rye, flat)	0
Nov. 25, 1998			
Random	2.5	2.0	2.5
Oriented[a]	0.0	0.0	22.5
Dec. 12, 1998			
Random	1.9	1.8	1.9
Oriented	0.0	0.0	6.5
Rye (1999, winter crop)			
Soil residue cover at seeding time (%, and residue type)	0	50 (sunflower, flat)	0
Aug. 3, 1999			
Random	3.7	2.1	3.5
Oriented	5.2	0.0	5.4
Nov. 11, 1999			
Random	2.5	2.0	3.0
Oriented	2.5	0.0	2.8

VT = vertical tillage, NT = no-till, CT = conventional tillage.
[a]The angle of oriented roughness with respect to the N was in all cases 90°.

2.3. Wind erosion calculation

The amount of material collected at each sampling point was calculated by integrating the equation that explained the relationship between the amounts of sediment with height, which takes the form

$$Q = aZ^{-c}, \tag{1}$$

where Q is the amount of sediment collected expressed in $\mathrm{kg\,m^{-2}}$, Z the height expressed in *m*, and a and c are constants (Zobeck and Fryrear, 1986a). This equation was integrated between the arbitrary lowest value of 0.000001 and 10 m height to calculate the amount of sediment passing through each sampling point. The top 10 m value was selected taking into account visual observations that indicated that this was approximately the highest sediment transportation height during storms. The amount of eroded material at each plot was calculated by subtracting the amount of sediment entering the plot from the amount of sediment leaving it. The amount of sediment entering the plot when the wind direction was 0° or 90° in relation to the N–S line was measured with the first windward BSNE sampling station, and the amount of sediment leaving the plot was measured with the last leeward sampler. When the wind direction was different from 0° or 90° in relation to the N–S line, sediment entering the plot was taken as the averaged amount of sediment collected by the two BSNE samplers placed to the windward wind position, while the sediment leaving the plot was taken as the averaged amount of sediment collected by the two samplers placed to

Table 2
Main characteristics of windstorms that occurred during measurements carried out for a summer (sunflower) and a winter crop (rye) and crop heights at different dates

Storm	Date (dd/mm/yy) and hour of sampling start	Date (dd/mm/yy) and hour of sampling conclusion	Storm duration (s)[a]	Mean wind speed ($km\,h^{-1}$)	Maximum wind speed	SD[b]	Wind direction
Sunflower							
1	25/11/98, 10.30 h	27/11/98, 10.00 h	45	9.9	14.7	3.6	NW
2	27/11/98, 18.00 h	30/11/98, 11.30 h	60	8.4	14.9	4.9	WNW
3	30/11/98, 17.00 h	01/12/98, 10.00 h	40	9.3	12.6	2.8	NW
4	01/12/98, 17.00 h	02/12/98, 16.00 h	480	12.0	18.8	5.1	S
5	03/12/98, 09.00 h	04/12/98, 09.30 h	30	7.3	10.6	4.4	NNW
6	04/12/98, 16.00 h	05/12/98, 09.30 h	900	17.2	22.2	7.9	SSE
7	07/12/98, 08.30 h	09/12/98, 08.30 h	960	11.8	28.6	8.8	WSW
8	09/12/98, 17.00 h	11/12/98, 09.00 h	600	11.2	23.7	7.3	E
9	11/12/98, 17.00 h	14/12/98, 16.30 h	120	5.6	19.9	10.4	ESE
			359[c]	10.3[c]	18.44[c]		
Rye							
1	03/08/99, 16.00 h	03/08/99, 17.00 h	120	15.8	15.9	0.1	N
2	06/08/99, 17.00 h	08/08/99, 16.00 h	600	17.6	25.3	3.2	W
3	10/08/99, 09.00 h	12/08/99, 18.00 h	480	17.8	22.5	2.3	SW
4	15/08/99, 11.00 h	16/08/99, 19.00 h	900	21.2	29.6	4.7	N
5	10/11/99, 07.00 h	10/11/99, 22.00 h	300	16.1	19.0	1.1	N
			480[c]	17.7[c]	22.4[c]		

[a]Time with wind speeds higher than 15 km/h.
[b]Standard deviation.
[c]Average value for the measurement period.

the leeward wind position. Positive values indicated gains and negative values indicated sediment losses from the field.

The amount of material collected was not corrected on the basis of BSNE sampling efficiency.

The sediment collected in each storm was stored by height and combined with the material collected in previous storms. At the end of the field measurement season the sediment was analyzed for nitrogen (Kjeldahl semi-micro-method, Schlichting et al., 1995)

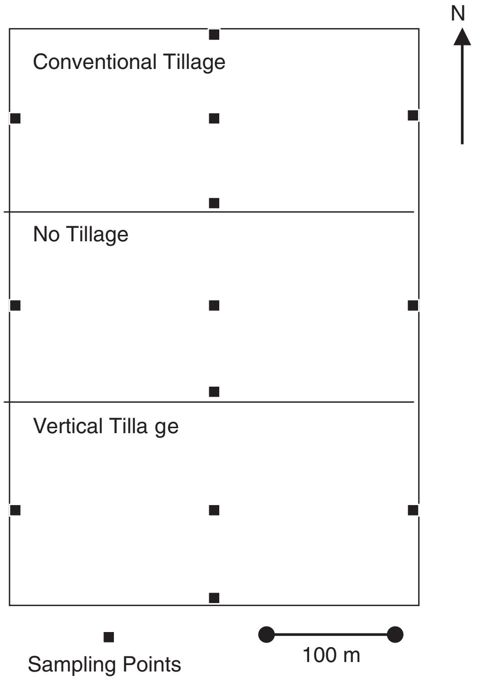

Fig. 1. Placement of samplers in the field and tillage systems developed.

and phosphorus (Bray and Kurtz I, Schlichting et al., 1995). The small amount of sediment collected (less than 2 g) did not allow replications for the determinations of its contents of nitrogen and phosphorus. The amount of nitrogen and phosphorus in the sediment at each height was calculated by multiplying the nutrient amount per kg soil by the amount of soil collected at that height. The resulting equations over the heights were integrated to obtain the amount of nitrogen and phosphorus at each sampling point by means of Eq. (1). The nutrient-enrichment ratio was calculated as the ratio of the nutrient content of the eroded sediment and the nutrient content of the surface soil (average phosphorus contents of four soil samples taken from the first 2.5 soil cm).

'Storm duration' was taken as the elapsed time with wind velocities greater than 18 km h^{-1} (the velocity considered as erodible by Fryrear et al. (1998)) within each measurement period. Mean minute wind direction and wind velocity data were obtained with an automatic meteorological station.

3. Results and discussion

Fig. 2 shows the amounts of sediment collected in the three tillage systems in both measurement periods. Losses and also accumulations of material were detected. Losses varied between 4 and almost 900 kg ha^{-1}, and accumulations between 3 and 580 kg ha^{-1}. Larger losses were observed in 1999 than in 1998. This agrees with higher storm wind speeds in 1999 (17.7 km h^{-1} in average) compared to storm wind speeds in 1998 (10.3 km h^{-1}, in average, Table 2).

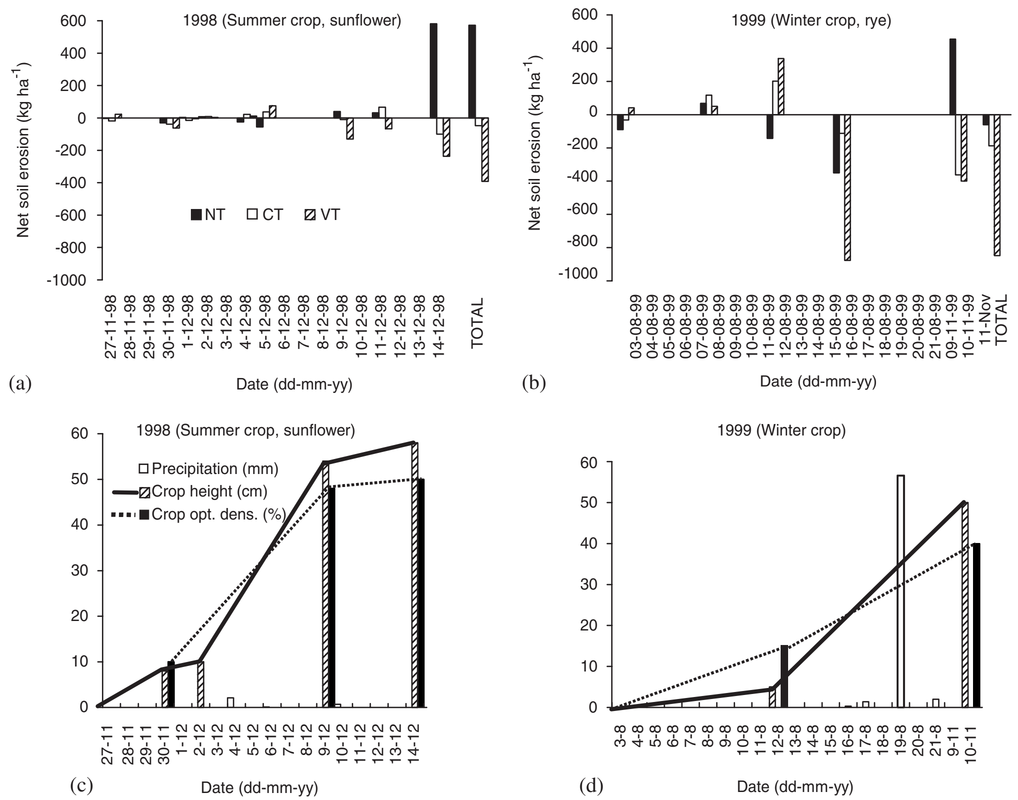

Fig. 2. Net soil erosion (accumulation = positive values, losses = negative values) in three tillage systems (VT = vertical tillage, NT = no till, CT = conventional tillage) during storms occurred in (a) 1998 (sunflower) and (b) 1999 (rye), and plant height, optical density and rains occurred during measurements in (c) 1998, and (d) 1999.

The erosion occurrence within each year was neither associated with canopy evolution of the growing crops nor with rains. Low erosion rates were detected during the first measurements, when crop heights and crop optical densities were low. Conversely, high erosion rates were measured at the end of both measurement periods when crop heights (60 cm for sunflower and 50 cm for rye) and optical densities (65% and 40%, respectively) were the highest. The lack of influence of rains on wind erosion rates is evidenced by high erosion rates measured on June 15, 1999 (876 kg ha^{-1}in CT) and low erosion rates measured on December 14, 1998 (390 kg ha^{-1} in CT). Rain conditions before both sampling dates were comparable, as the first measurement was done after 12 days without rains, and the last after 17 days with little low rain (2.9 mm).

In 1999 all tillage systems showed losses ordered in the sequence from high to low: VT (847 kg ha^{-1}) > CT (187 kg ha^{-1}) > NT (61 kg ha^{-1}). In 1998 this sequence was the same, VT (392 kg ha^{-1}) and CT (47 kg ha^{-1}) showed losses but NT had accumulation (571 kg ha^{-1}). The losses from VT and CT were higher in 1999 than in 1998, in agreement with the higher wind speeds and lower soil surface coverage with plant residues in 1999.

NT lost the least sediment in 1999 and showed accumulations of sediment in 1998, while VT presented the largest losses in both measurement periods. This was probably related to high soil plant residue cover in NT and to the low soil surface roughness in LV (Table 1). The high amounts of residue caused a reduction of the material eroded and also acted as a trap for the sediment moving from neighboring plots in NT. Sediment accumulation in NT occurred on December 14, 1998 and on November 10, 1999, when the highest wind velocity was relatively low (19.6 km h^{-1} on December 14, 1998 and 19.0 km h^{-1} on November 10, 1999). Under such conditions erosion from VT occurred and transported particles were trapped by NT. On August 16, 1999, maximum wind speed was high enough (29.6 km h^{-1}) to erode the soil in both tillage systems, and to produce the maximum erosion amount in VT (876 kg ha^{-1}).

Erosion was lower in CT than in VT, particularly in the storms that occurred in December 9, 12, and 14, 1998, and August 16 and November 10, 1999. This was probably related with the higher oriented soil surface roughness that CT presented at the start and the end of both measurement periods.

Fig. 3 shows the relative enrichment of total nitrogen concentration (%) and available phosphorus concentration (%) in relation to surface soil concentration as a function of height in the sediment collected during measurements carried out in 1998 and 1999. In agreement with results of Zobeck et al. (1989) the enrichment of both elements increased with height in all cases. At lower heights values were similar in both measurement periods but they were different at greater heights for both elements. This tendency was more pronounced for nitrogen in 1999 and phosphorus in 1998. Such differences may be related

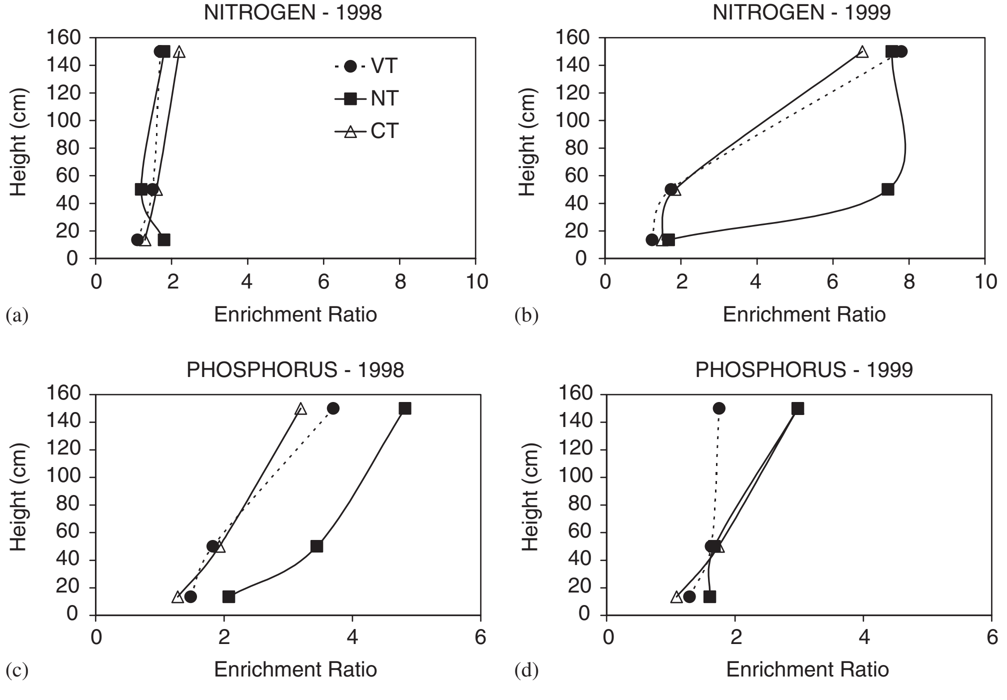

Fig. 3. Enrichment ratios of nitrogen in (a) 1998 and (b) 1999, and of phosphorus in (c) 1998 and (d) 1999, in three tillage systems (VT = vertical tillage, NT = no tillage, CT = conventional tillage), as a function of height.

to an interaction between wind speed and the tendency of each element to accumulate in different size fractions. In 1998, the average nitrogen concentration of all tillage systems varied by 20% between heights (from 0.15% at 13.5 cm height to 0.18% at 150 cm), while in 1999 it varied almost 270% (from 0.20% at 13.5 cm height to 0.74% at 150 cm height). Aimar (2001) found that organic matter contents, which are closely linked to nitrogen contents in the studied soils (Buschiazzo et al., 1991), accumulated in the middle sized fractions (50 μm) or was uniformly distributed in the coarsest size fractions of the studied soils. Others have found that organic matter accumulates in macroaggregates (>250 μm) rather than in microaggregates (<250 μm) (Tisdall and Oades, 1982). It is known that the grain size distribution of the sediment becomes finer with height as a consequence of their lighter weight and the total amount of sediment decreases in the same direction (Zobeck et al., 1989, and Aimar, 2001). However, when wind velocity increases, heavier and coarser aggregates will be transported to greater heights (Chepil and Woodruff, 1963). Therefore, under high wind velocity conditions, transportation of coarser and more nitrogen-enriched particles is expected. This was probably the case of storms of 1999 (Table 2) where nitrogen enrichment of the sediment at higher heights occurred.

Phosphorus showed the opposite tendencies to that for nitrogen. In 1998, phosphorus varied more than 90% with height (from 38 mg kg^{-1} at 13.5 cm height to 73 mg kg^{-1} at 150 cm) and in 1999 only 50% (from 25 mg kg^{-1} at 13.5 cm height to 38 mg kg^{-1} at 150 cm). As phosphorus is strongly accumulated in the finest sized fractions of the studied soils (Prüess et al., 1992), it can be deduced that at greater wind speeds, like those of 1999, the relative amount of the coarsest particles increases at higher heights, decreasing the concentration of phosphorus in the sediment.

In 1998, the nitrogen content in the sediment followed in the sequence NT < VT < CT, while phosphorus contents showed the opposite tendencies at most heights. This agrees with the probable lower speeds that occurred in NT than in the other tillage systems at similar heights, as residue cover of this tillage system acted like a wind barrier. The largest nitrogen accumulation in sediments from NT at the lowest height was probably produced by the accumulation of coarse particles moving by saltation from neighboring plots.

In 1999, concentrations of nitrogen were highest in NT at lower heights, because of the movement of finer particles at this level, as a consequence of the wind barrier effect produced by plant residues. On the other hand, phosphorus concentrations of VT in 1999 were lowest at greater heights, in accordance with higher wind speeds that occurred in this tillage system, as a consequence of the lack of soil plant cover and the lower soil roughness of the soil, mainly before the last storm (November 10).

With lower wind speeds as in 1998, the nitrogen concentration in the sediment of all tillage systems was, at the greater heights, twice that of the original soil (0.10%), while in the high wind velocity period of 1999 it was almost seven times higher. On the other hand, phosphorus concentration in the sediment in 1998 was three times higher than in the soil, and almost doubled that of the soil in 1999. These results indicate that the relative nitrogen enrichment of the sediment will be more variable with wind speed, being higher at highest speeds, than the relative enrichment of phosphorus, which will be more constant with variations of the wind speed. We conclude that lower speed windstorms will erode relatively more phosphorus than nitrogen. When high-speed windstorms occur, nitrogen becomes more susceptible to removal from the soil because wind speed seems to be the variable that regulates the amounts of nitrogen lost.

4. Conclusions

The present results allow us to conclude that in a fine sandy loam Entic Haplustoll of the Semi-arid Pampa of Argentina, soil losses by wind erosion during a period with high speed winds, and no precipitation along most of measurement period, occurred in all tillage systems, being lower in those with higher plant residue coverage (NT and to a lower extent CT). Soil losses during a period with low speed winds were low and the tillage system with high residue coverage (NT) showed accumulations of sediment.

Nitrogen concentration in the sediment collected at greater heights increased and phosphorus concentration decreased with wind speed. We suspect that this was due to the accumulation of nitrogen in coarse and of phosphorus in fine aggregates. The nitrogen enrichment of the sediment increased with wind speeds and the phosphorus enrichment decreased.

Lower-speed windstorms will erode relatively more phosphorus than nitrogen. When high-speed windstorms occur, nitrogen becomes more susceptible to removal from the soil because wind speed seems to regulate the amounts of nitrogen lost.

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